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Diagnostic Testing For the Determination of Quality of Live-Line Ropes

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Abstract

This paper provides details of a testing program devised for the selection, by a power utility, of the most appropriate live-line rope from seven different new specimens. A wide range of electrical tests and varying environmental conditions were utilized. This represented a considerable challenge as test standards for evaluating rope designated for live-line work are not easily accessible and do not specifically cover the range of materials now offered. The testing includes leakage current, breakdown strength and dissipation factor measurements. Findings from these tests are presented in this paper and a general methodology for ranking rope based on these measurements is also discussed in detail.

Keywords
Live line ropes, leakage current, breakdown voltage, dissipation factor.

1 INTRODUCTION

The reliance of society on energy has never been greater, as consumers demand a continuous, reliable and cheap supply of electricity. With the advent of the computer age and electrical appliances for every need, the requirement for an uninterrupted supply of power is at a premium. Maintenance on live transmission and distribution lines is very important today because of high consumer expectations. Performing live-line maintenance puts linesmen at risk if safety equipment is faulty or correct procedures are not adhered to. Many safety devices afford protection to linesmen including hot sticks and rubber gloves, but an important safety item required by linesmen has had little previous investigation. We refer to the live-line rope.

Current literature on the testing of live-line rope is scarce. Testing procedures are available in ASTM F1701-96 [1], but these procedures only cover the testing of unused polypropylene thus limiting material selection. Some test experience at Bonneville Power Administration [2] also provided some information, but deals with polypropylene and polydacron only.

The objective of our test program was to compare a variety of different rope materials subjected to a number of different environmental conditions. Sustained performance of samples subjected to wet conditions being of significant note. Findings from this test program are reported in this paper. A number of findings suggest the limitation of current standards and this will also be highlighted in this paper. By subjecting samples to conditions that may be experienced in the field, an overall picture of performance can be formulated. It is hoped that power utilities can make informed decisions about which tests to utilize in selecting rope material to suit their required applications.

2 TEST SAMPLES

Test samples were taken directly from production deliveries, that is, straight from the roll. As instructed by the standard ASTM F1701-96, specimens 8 ft in length were cut from the rolls with particular care taken not to handle the specimens within the 5 ft test area.

Seven different rope materials were subjected to a range of electrical tests and descriptions of these can be found in Table 1. Each specimen is allocated a sample number for ease of referral throughout this paper.

Table 1 – Rope Specimens

High Density 3-Strand Polypropylene	*Sample A*
3-Strand Polydacron	*Sample B*
9/16 Polytron	*Sample C*
Nylon Static 11mm	*Sample D*
Waxed Polyethylene 3-Strand	*Sample E*
Shielded Kevlar Stringing Cable	*Sample F*
3-Strand Polydacron Cord	*Sample G*

Figure 1 illustrates the seven specimens listed in Table 1 with Sample A on the left through Sample G on the right.

A B C D E F G
Figure 1 – Rope Specimens

3 EXPERIMENTAL MEASUREMENTS

The electrical tests conducted on the above specimens included AC leakage current on wet and dry samples, AC dielectric breakdown voltage on wet, dry, soiled and salt water immersed samples, capacitance, dissipation factor and DC resistance of dry samples.

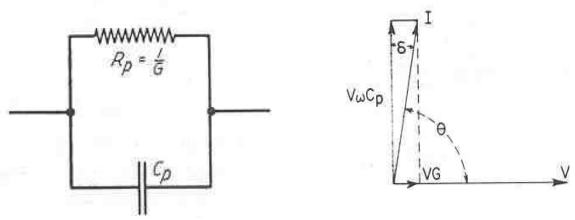
3.1 AC Leakage Current Measurement

Rope samples of 8 ft in length were suspended vertically and kept taut with a 10lb weight. Electrodes designed to shield the majority of stray capacitances were separated by 1ft (305mm) [1]. The brass plates have a diameter of 500mm and have copper tubing of diameter 12mm silver soldered around the circumference of the brass plates to prevent any edge discharge. Holes of diameter 45mm are present in the centre of each plate to allow the fixing of the electrode arrangements. The top plate is energized at high potential hence a brass nut of diameter 52mm and centre hole of 8.2mm can be fixed to enable attachment to the sample. The lower plate is insulated from the sample with a nylon insulating support of diameter 52mm. This support has a brass insert to provide the electrical connection to the sample. A separate brass lug is soldered onto the outside face of the lower plate to provide an earth connection. Figure 2 illustrates the described test arrangement. After each sample had been placed in the test cell, plates were checked for distance of separation and levelness.

Figure 2 – AC Leakage Current Test Arrangement

Dry samples were subjected to a slow rate of rise voltage from 0–100kV in not less than 5 or greater than 15 seconds. Upon reaching 100kV, voltage is held constant for a period of 5 minutes. If at the end of this time the leakage current is below 100μA and stable the specimen is deemed to have passed [1].

Wet samples are subjected to the same standard as the dry samples with the supply voltage reduced to 50kV. Samples were wet in 300mm of water of 100Ωm resistivity for the specified time of 15 minutes [1]. The measured AC leakage current of the live-line rope samples is a complex value comprising resistive and capacitive components. By modelling the samples as a resistor and a capacitor connected in parallel, (Figure 3(a)) and vector representation, (Figure 3(b)) we can write:



(a) (b)
Figure 3- Insulation representation of ropes and vector diagram.

$I_{COMPLEX} = I_R + I_C$
We know that $I_R = V/R$ hence we write:
$I_{COMPLEX} = V/R + I_C$ and $I_C = jV\omega C$
Hence $I_{COMPLEX} = V/R + jV\omega C$

This will enable direct comparison between measured values and calculated values of complex leakage current.

3.2 Dielectric Breakdown Strength Measurement

For this test the plates were removed and the samples were tested with an electrode separation of 305mm as per the Standard [1]. The dry samples were exposed to a slow rate of rise voltage from zero until dielectric failure occurred [3]. It was noted that the dry samples experienced similar breakdown voltages to each other at this electrode separation, which were also similar to the expected air gap breakdown voltage. Therefore it was decided to test the air gap breakdown voltages at electrode separations of 305mm to 800mm in 50mm increments. This would then enable a direct comparison between samples and the air gap.

Once this base line had been established, all specimens were tested three times at each electrode separation distance with the average recorded for analysis. Figure 4 shows the apparatus setup for the dielectric breakdown voltage test.

Figure 4– Dielectric Breakdown Voltage Set-up

The specimens were suspended from a crane and held taut with the same 10lb weight. Testing methods were obtained from ASTM D 149-97a [3] and ASTM D 150-95 [4].

3.3 Capacitance and Dissipation Factor Test

Capacitance and dissipation factor (tan δ) measurements were performed using a "Capacitance and Dissipation Factor Test Set" by Tettex Instruments. This equipment is based on Schering Bridge principle with digital circuitry. Balancing the bridge arrangement was attained with a standard gas compressed capacitor. Samples were tested at an electrode separation of 305mm at voltages of 20kV and 50kV to enable comparisons. The measured values of capacitance can be used in the determination of the capacitive leakage current I_C, as shown for leakage current calculations.

3.4 Resistance and Resistivity Measurement

The resistances of the specimens were measured using a digital 5kV Megger with the results used to calculate resistivity. The resistance readings are also useful in determining the resistive current I_R as in the leakage current calculations. Resistivity is an accepted electrical value when rating an insulating material and was calculated using the following relationships:

$R = \rho l/A$

Where R = DC Resistance in Ω

ρ = Resistivity in Ωm

l = Length of sample in metres

& A = Cross sectional area of sample

4. RESULTS OF TESTS

4.1 AC Leakage Current

All dry samples tested in accordance with [1] displayed values under 100μA and therefore were considered to have passed. Values ranged from 18μA for Sample F through to 35μA for Sample C.

When samples were exposed to water immersion much different values were experienced. Figure 5 shows the performance of the wet samples.

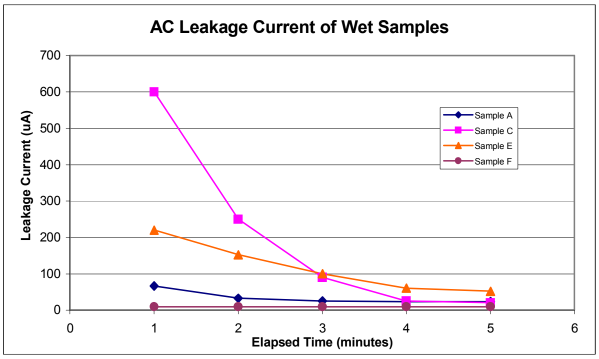


Figure 5 – Wet AC Leakage Current

Values were recorded each minute for the duration of the 5-minute test. Only four samples are presented as samples B, D and G flashed over before the 50kV supply could be reached. It is noted that the initial leakage currents are higher than the specified 100μA with the values decreasing as the heat generated from the supply voltage drives the moisture from the samples. It can also be seen that at the completion of 5 minutes, the remaining samples are below 100μA and stable, hence pass the test. The authors feel that initial values of leakage current are just as important as the final readings, as they pose a greater risk to worker safety. This is not specified in the standard [1].

4.2 Dielectric Breakdown Voltage

All specimens were tested in accordance with [1], [3] and [4], for dry, wet, soiled and salt water immersed conditions. The reason for the variation in conditions was to simulate the range of extremes a live-line rope may be subjected to in the field. For instance; soiled samples attempted to mimic general handling and placement on the ground whereas salt water immersed samples attempted to replicate line work in coastal areas where salt spray is present.

As previously mentioned, the dry specimens displayed results similar to what would be expected for air gap breakdown for the same electrode separation. Figure 6 shows the seven samples plotted against the air gap flashover voltage.

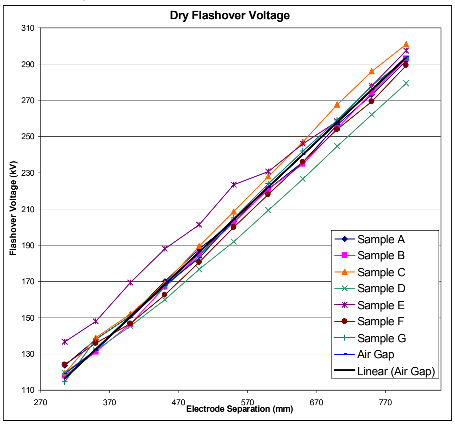


Figure 6 - Dry Flashover Voltage

The first point of note from the values displayed above is that the relationship between electrode separation (mm) and flashover voltage (kV) is linear. It was the relative closeness between these values and the air gap values that raised the question of whether the samples were flashing over or indeed the air gap was breaking down.

The exceptions were Sample D, which displayed values consistently lower than the air gap values, and Sample F, which had values higher than air gap values. It became evident that this test was not going to give us definitive differences to enable selection of any one particular sample.

Samples exposed to wet conditions behaved much differently as expected. Figure 7 shows the flashover voltages of six of the seven samples. Sample F was omitted from this test as it has a waterproof polymer shield surrounding the Kevlar core making water ingress impossible.

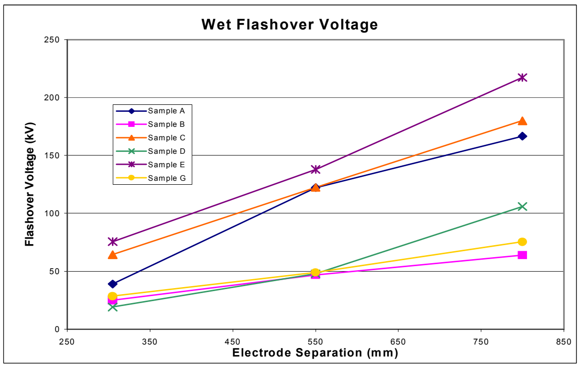


Figure 7 – Wet Flashover Voltage

It is observed that the samples have separated into two distinct groups as far as flashover performance is concerned. Samples E, C and A exhibited much higher flashover voltages at the three distances than Samples B, D and G. It is noted here that Samples B, D and G also flashed during the leakage current tests. Sample E was assisted by its wax coating that limited the amount of water ingress. After repeated exposures it was noted that wax coating began to deteriorate.

All samples were then subjected to soiling in the attempt to mimic field conditions. Figure 8 showed that the soiling had little overall effect on the flashover voltage values.

If we view the values obtained at an electrode separation of 800mm we can see that although the values are similar to those in the dry flashover voltage test, the order of highest to lowest has changed. Sample C for instance had the highest flashover voltage at this distance in the dry test but, because of its open weave construction, has retained more dirt and is significantly affected. The samples with tighter weaves did not deviate appreciably enough to be significant.

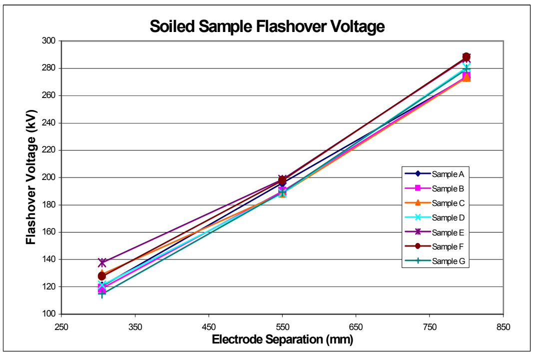


Figure 8 – Soiled Sample Flashover Voltage

Performing soiled sample tests also introduces other variables such as soil resistivity. It becomes difficult to predict how a soiled live-line rope will behave unless a relationship between the soil resistivity and electrical performance can be determined. This was outside the scope of this testing.

By immersing the samples in the same water as for the wet tests but with the addition of salt, we were able to perform flashover voltage tests that imitate conditions of live work in coastal areas. The concentration of salt used was 224g/L in accordance with AS 1931.1 [5]. This concentration far exceeds that of seawater, but achieving appreciable differences was desired. It was decided to let the samples dry completely before testing, as a comparison to the dry flashover results was more meaningful. Also, it is hoped that a linesman would be less likely to use a wet live-line rope as opposed to one that had been exposed to salt spray and then dried. Figure 9 shows the flashover voltage values obtained in this test.

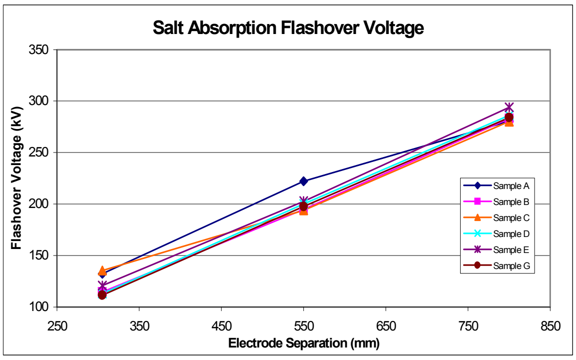


Figure 9 – Salt Absorption Flashover Voltage

The results obtained for this test were extremely similar to the values obtained for the corresponding dry test. The order from highest to lowest has changed marginally, but not enough to be significant. A bright orange flashover as opposed to the previously seen blue flashover was the main appreciable difference.

4.3 Capacitance and Dissipation Factor

Table 2 – Capacitance & Tan δ Measurement

	Capacitance and Dissipation Factor			
	20 kV		50 kV	
	Capacitance (pF)	Dissipation Factor	Capacitance (pF)	Dissipation Factor
Sample A	1.306	0.0875	1.59	0.658
Sample B	1.408	0.168	1.666	0.756
Sample C	1.218	0.0922	1.531	0.689
Sample D	1.13	0.1081	1.414	0.702
Sample E	1.246	0.0786	1.589	0.685
Sample F	1.196	0.0649	1.53	0.663
Sample G	1.24	0.0997	1.604	0.663

Specimens were tested for capacitance and tan δ measurements as described earlier. The capacitance value was used to calculate the capacitive current I_C.

Table 2 shows the capacitance and tan δ values. It can be seen that for 50 kV supply voltage the dissipation factor is extremely high. This would indicate that all samples are extremely lossy.

4.4 Resistance and Resistivity

Table 3 displays the recorded values of resistance and the calculated resistivity for all samples. Samples B, D and G recorded the lowest resistance values. It is also noted that these were the samples the flashed over during wet leakage current tests and displayed the lowest flashover voltages during dielectric breakdown testing. Sample F also exhibited a relatively low resistance, but because of its Kevlar coating, its performance under wet conditions could not be determined unlike the aforementioned samples.

Table 3-DC Resistance and resistivity

DC Resistance and Resistivity				
	Length (m)	A (m^2)	Resistance (Ω)	Resistivity (Ωm)
Sample A	0.305	1.42×10^{-4}	> 505GΩ	2.35×10^{8}
Sample B	0.305	1.03×10^{-4}	75GΩ	2.53×10^{7}
Sample C	0.305	2.98×10^{-4}	> 505GΩ	4.93×10^{8}
Sample D	0.305	1.17×10^{-4}	110GΩ	4.22×10^{7}
Sample E	0.305	2.03×10^{-4}	> 505GΩ	3.36×10^{8}
Sample F	0.305	6.79×10^{-5}	137GΩ	3.04×10^{7}
Sample G	0.305	1.23×10^{-4}	348GΩ	1.40×10^{8}

Using the values of resistance and capacitance, we can compare the measured complex dry leakage current with their individual capacitive and resistive components. Table 4 demonstrates this.

It can be seen that the measured complex currents are always lower than that of the calculated values. This is due to the parallel plates not being used for the resistance and capacitance measurements. There was no protection against stray capacitances but the comparison still shows the values fall within the same order of magnitude. The phase angles recorded indicate that the complex leakage current is almost entirely capacitive in nature, which is to be expected.

Upon completion of this testing program, samples have been ranked based on their overall performance. Table 5 in Appendix A lists these findings.

Table 4 – Resistive and Capacitive Currents

	$I_{COMPLEX}$ Measured (μA)	I_R=V/R (μA)	I_C=jVωC (μA)	$I_{COMPLEX}$ Calculated (μA)
Sample A	22	0.198	j41.03	41.03∠89.7°
Sample B	25	1.33	j44.23	44.25∠88.3°
Sample C	35	0.198	j38.26	38.26∠89.7°
Sample D	20	0.909	j35.5	35.5∠88.5°
Sample E	24	0.198	j39.14	39.14∠89.7°
Sample F	18	0.730	j37.57	37.57∠88.9°
Sample G	22	0.287	j38.96	38.96∠89.6°

5 CONCLUSIONS

From the testing performed, it is clear to see that it is possible to select a ‘most appropriate’ live line rope but that not all tests are equally discriminating. Our findings from the leakage current under wet conditions suggest that initial values of leakage current are just as important as the final readings, as they pose a greater risk to worker safety.

If we view the values obtained at an electrode separation of 800mm we can see that although the values are similar to those in the dry flashover voltage test, the order of highest to lowest has changed. Sample C for instance had the highest flashover voltage at this distance in the dry test but, because of its open weave construction, has retained more dirt and is significantly affected. The samples with tighter weaves did not deviate appreciably enough to be significant.

It became evident that breakdown voltage test under dry condition did not provide any definitive differences to enable selection of any one particular sample. However, samples exposed to wet conditions behaved much differently and was found to be more distinctive for selection purpose. A number of samples (Samples B, D and G) showed the lowest resistance values. These were the samples flashed over during wet leakage current tests and displayed the lowest flashover voltages during dielectric breakdown testing. Hence we find that there is a need for current testing standards to be reviewed to encompass a wider range of rope material, to include additional tests where necessary and to cover routine re-testing after a period of service in the field.

6 REFERENCES

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Appendix A

Table 5 – Sample ranking

Ranking	Sample	Justification
1	Sample E	Highest wet & high dry flashover voltages. Low wet & dry AC leakage currents.
2	Sample A	High wet & dry flashover voltages. Moderate dry & very low wet AC leakage currents.
3	Sample C	Highest dry & high wet flashover voltages. Highest dry & wet AC leakage currents.
4	Sample F	Dry & wet flashover voltages equal but low for dry and high for wet. Best for AC leakage currents.
5	Sample G	Lowest dry & second lowest wet flashover voltages. Low dry AC leakage current. Flashover for wet AC leakage current at 30kV.
6	Sample D	Moderate dry & low wet flashover voltages. Low dry AC leakage current, but flashed over at 15kV for wet AC leakage current
7	Sample B	Moderate dry & lowest wet flashover voltage. High dry AC leakage current. Flashed over at 30kV for wet AC leakage current. Never use on EHV lines.